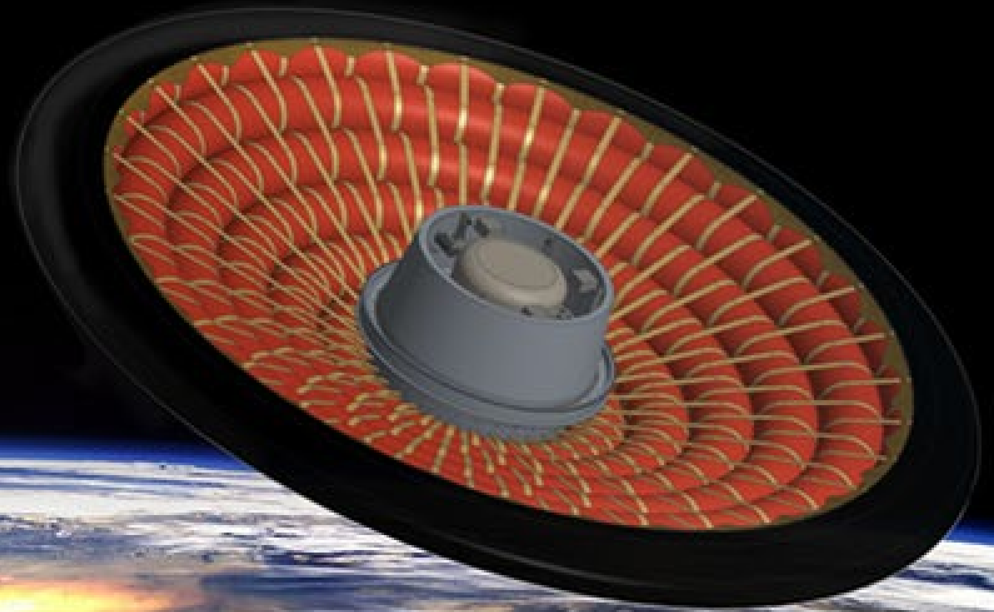
Fiber Optics Sensing System (FOSS) deployment on Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID)



Hon M. (Patrick) Chan, NASA Armstrong Flight Research Center

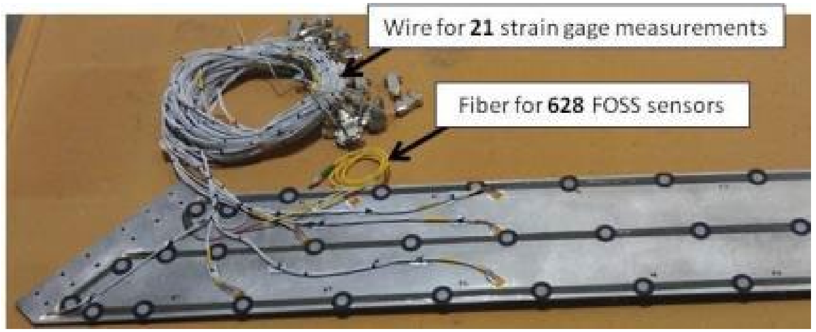
AIAA Science and Technology Forum and Exposition

Bayhill 23, AFM-13

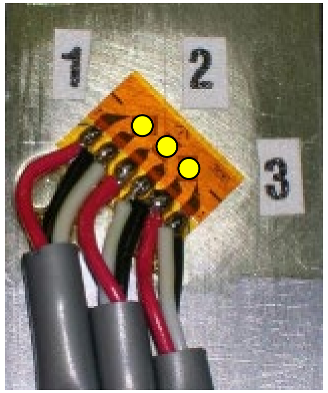
Wed, Jan 10th, 2024

Why Choose Fiber Optic Sensors over Resistive Gages?

One Of These Things (is Not Like The Others)

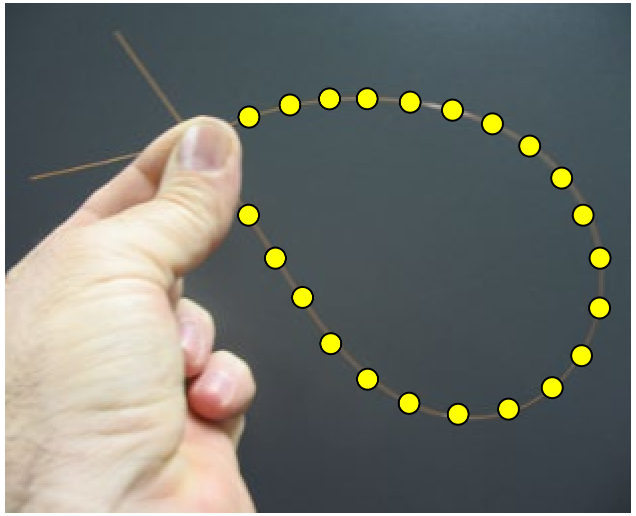


(Heavy)



(Big)

(Hard)

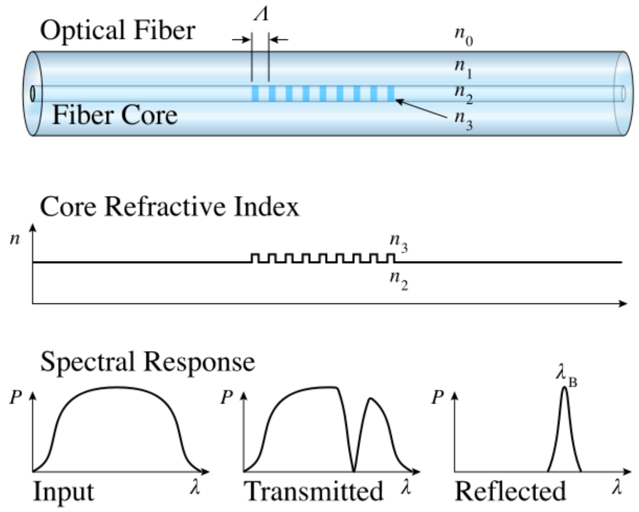


(Light, small, easy)

Fiber Bragg Grating (FBG) as sensor

Principle

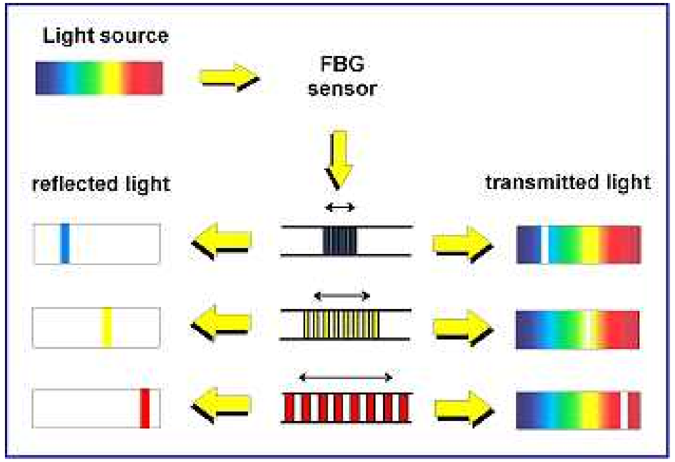
- Fiber Reflector that reflects a particular wavelength and transmit all others
- Bragg Wavelength: λ_B=2$n_e\Lambda$



Measuring Strain(ε) or Temperature (ΔT) via FBG sensor

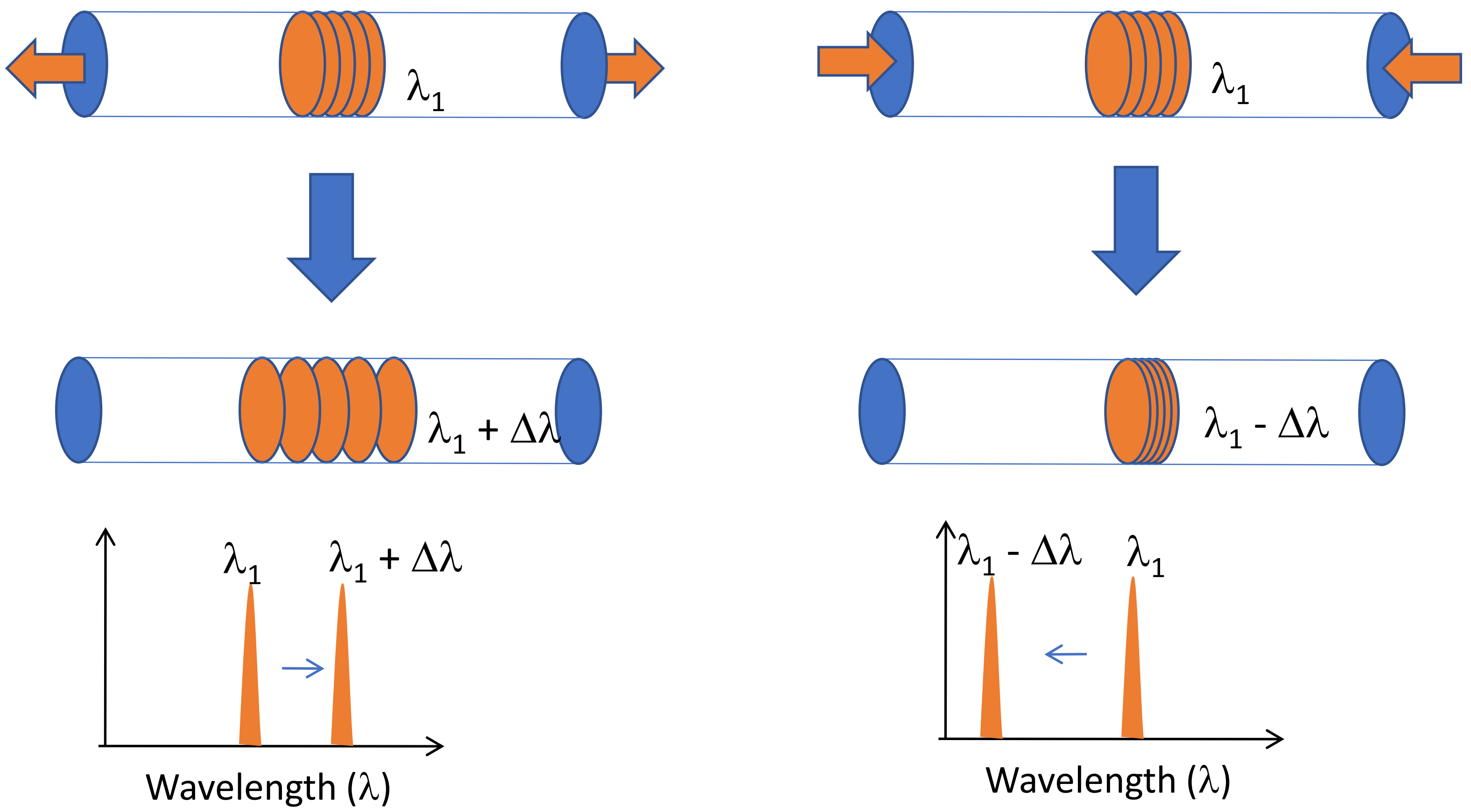
$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\varepsilon + (\alpha_\Lambda + \alpha_n)\Delta T$$

- $\Delta\lambda_B$= change in Bragg wavelength <u>due to environmental change</u>
- λ_B= Initial Bragg wavelength of FBG
- p_e= strain-optics coefficient
- α_Λ = Thermal expansion coefficient
- α_n = thermo-optic coefficient

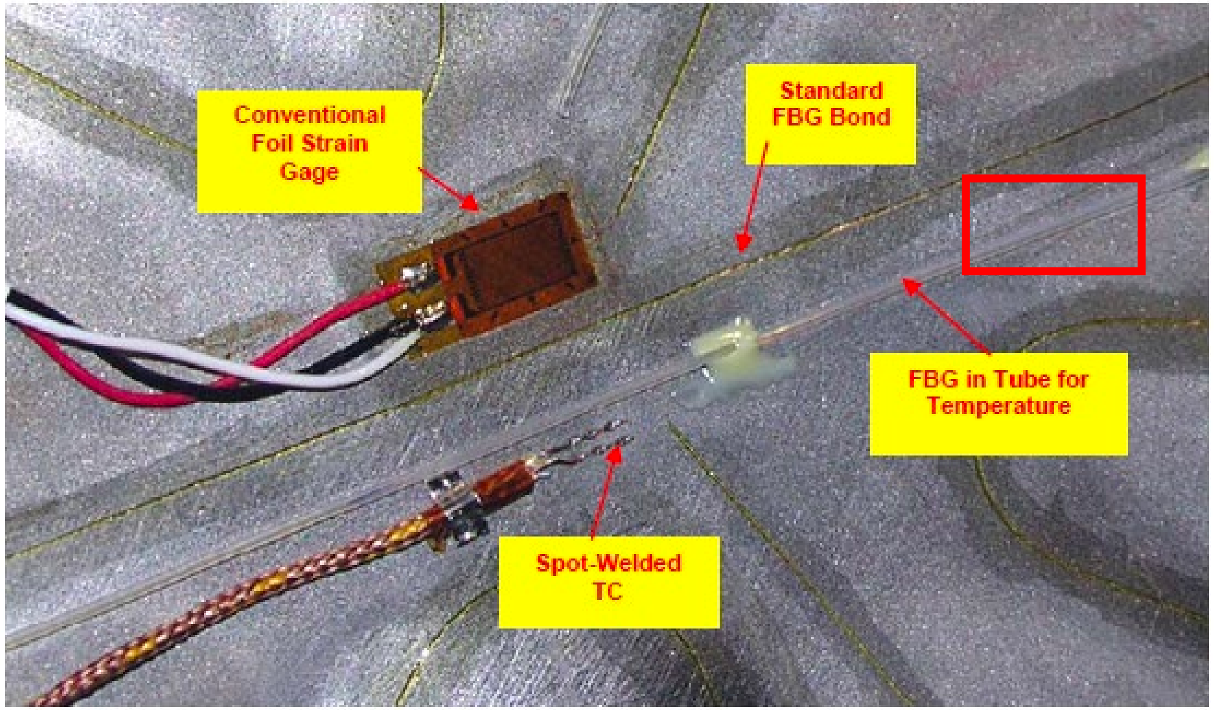


How do FBG sensors works?

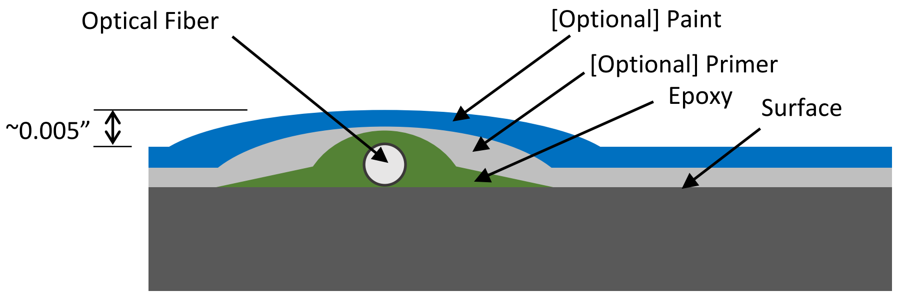
- Like an accordion → change in Bragg Wavelength



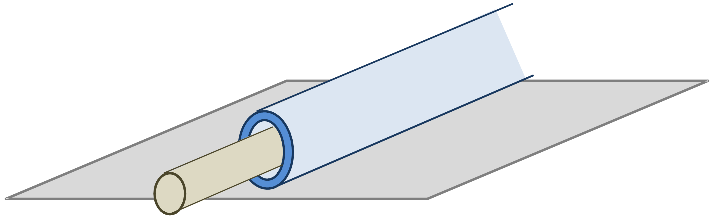
How to implement FBG into structural health monitoring (SHM)



Side-by-side comparison of fiber-based strain and temperature sensor vs convention foil-type strain gage and thermocouple



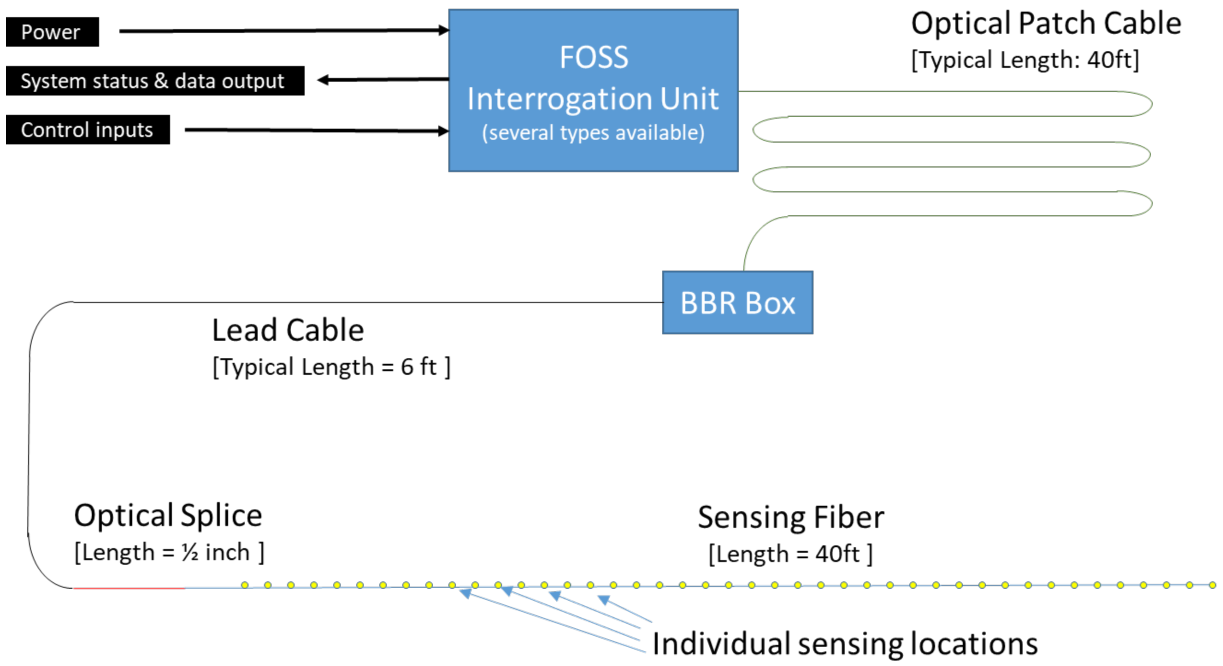
Layers of optical fibers for strain bonding.



An FBG being loosely coupled to measure temperature without measuring mechanical strain generated from the surface.

NASA's Unique FBG Interrogation Technique: OFDR

- Optical Frequency Domain Reflectometry (OFDR):
  - Based on laser interferometry
    - Single Longitudinal mode laser needed
  - Involves signal processing
    - Fourier Transform/inverse Fourier Transform
  - Use weak reflectivity FBG
    - Typical WDM FBG's R=80%
    - Typical OFDR FBG's R=0.05%
  - So why use OFDR for sensing instead?
    - Thousands of sensors in 1 single fiber
    - High spatial density (sensor every ¼" increment), see LOFTID results.

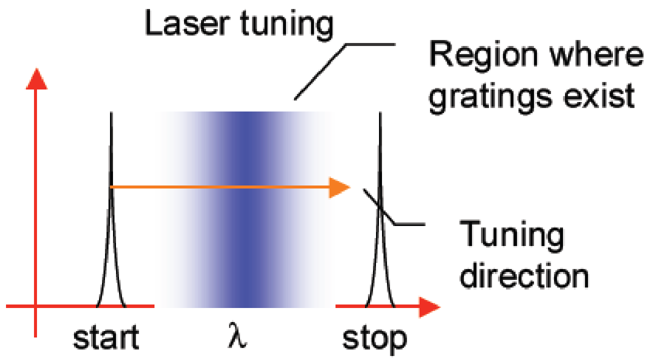


Optical Frequency Domain Reflectometry

- All FBGs are written at the same wavelength (λ_B), instead of each having a unique wavelength (WDM)
  - Multiplexing of hundreds of sensor in single fiber
- A narrowband wavelength tunable laser source is used to interrogate multiple sensors.
- Each FBG sensor <u>is only ½ inch long</u>

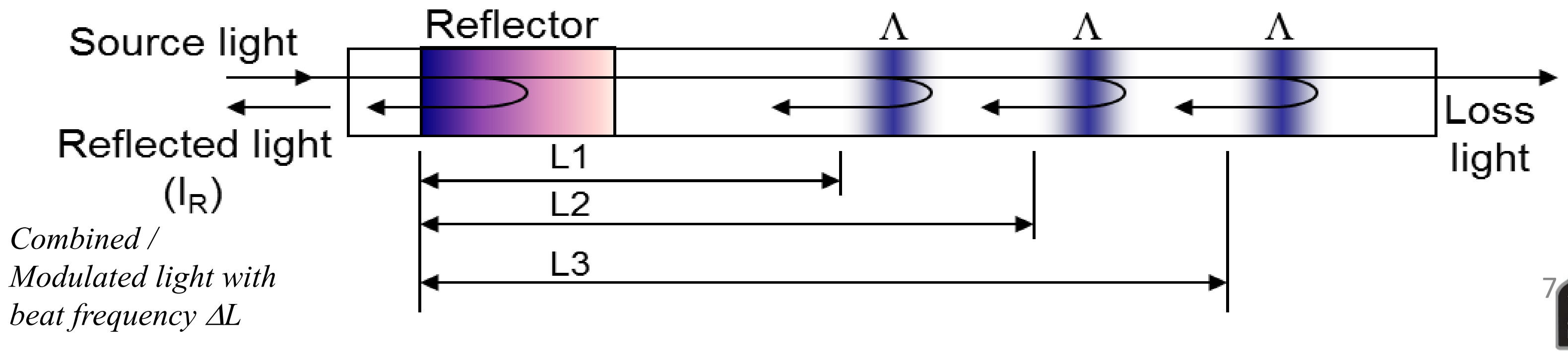
Principle

- Combine 2 coherent waves to generate a beat frequency
  - This is an unique beat frequency based on the length difference ΔL
- Multiple sensors with unique beat frequencies (ΔL_{fbg}) are captured
- In Fourier Domain each sensor with unique frequency is separated, and iFFT to obtain its design wavelength (λ_B)

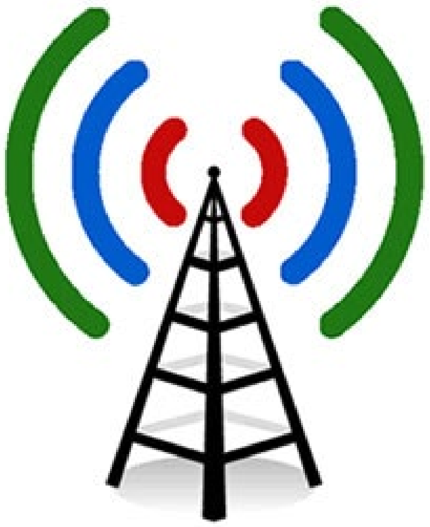


$$I_R = \sum_i R_i Cos(k2n_0L_i) \qquad k = \frac{2\pi}{\lambda}$$

R_i – spectrum of i^{th} grating
n_0 – effective index
L – path difference
k – wavenumber



Layman’s Term: Tuning your favorite radio station!

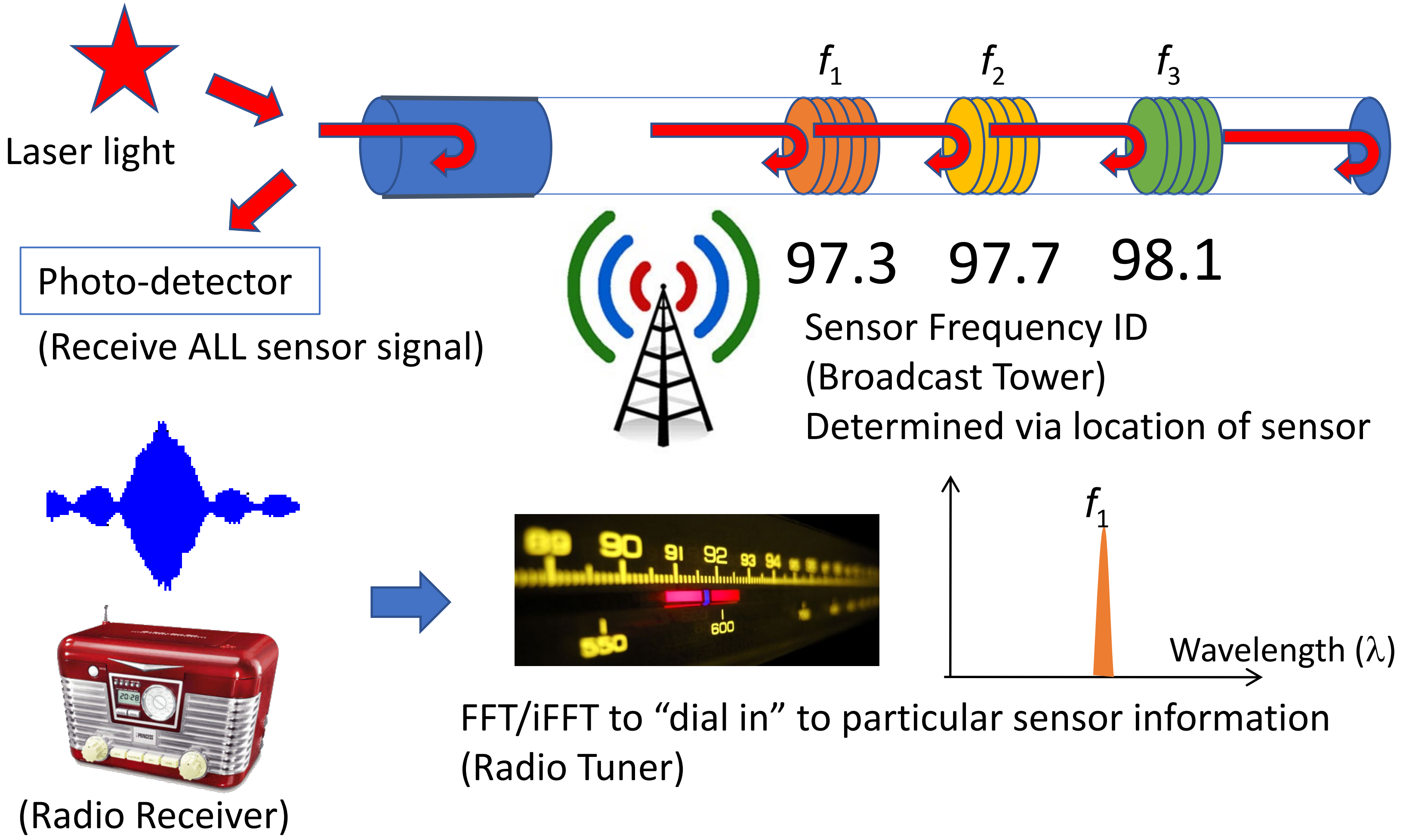


Multiple frequencies
are broadcasted on airwave

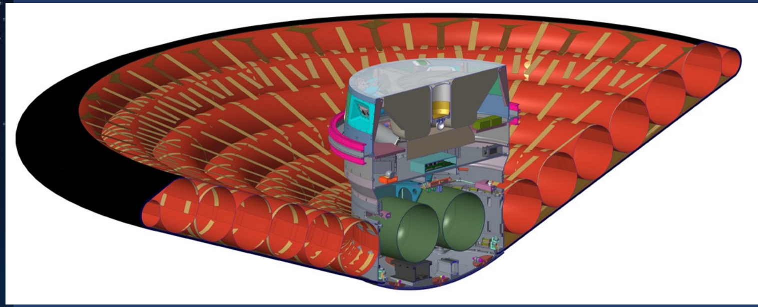
Radio receives ALL frequencies

Radio tuner accepts ONE frequency

Radio analogy to Optical Frequency Domain Reflectometry



LOFTID Background



A New Kind of Heat Shield

- After more than a decade of development of Hypersonic Inflatable Aerodynamic Decelerator (HIAD) technology, including two suborbital flight tests, the LOFTID orbital flight test is the next step. This return from orbit demonstration provides an entry environment relevant to many potential applications, paving the way for its use on future missions. The LOFTID re-entry vehicle, at 19.7 feet (6 meters) diameter, is the largest blunt body aeroshell to ever go through atmospheric entry.

FOSS project - LOFTID

- A launch capable version of FOSS is being developed to support LOFTID
- FOSS is integrated into LOFTID to monitor nose-cone temperature during reentry

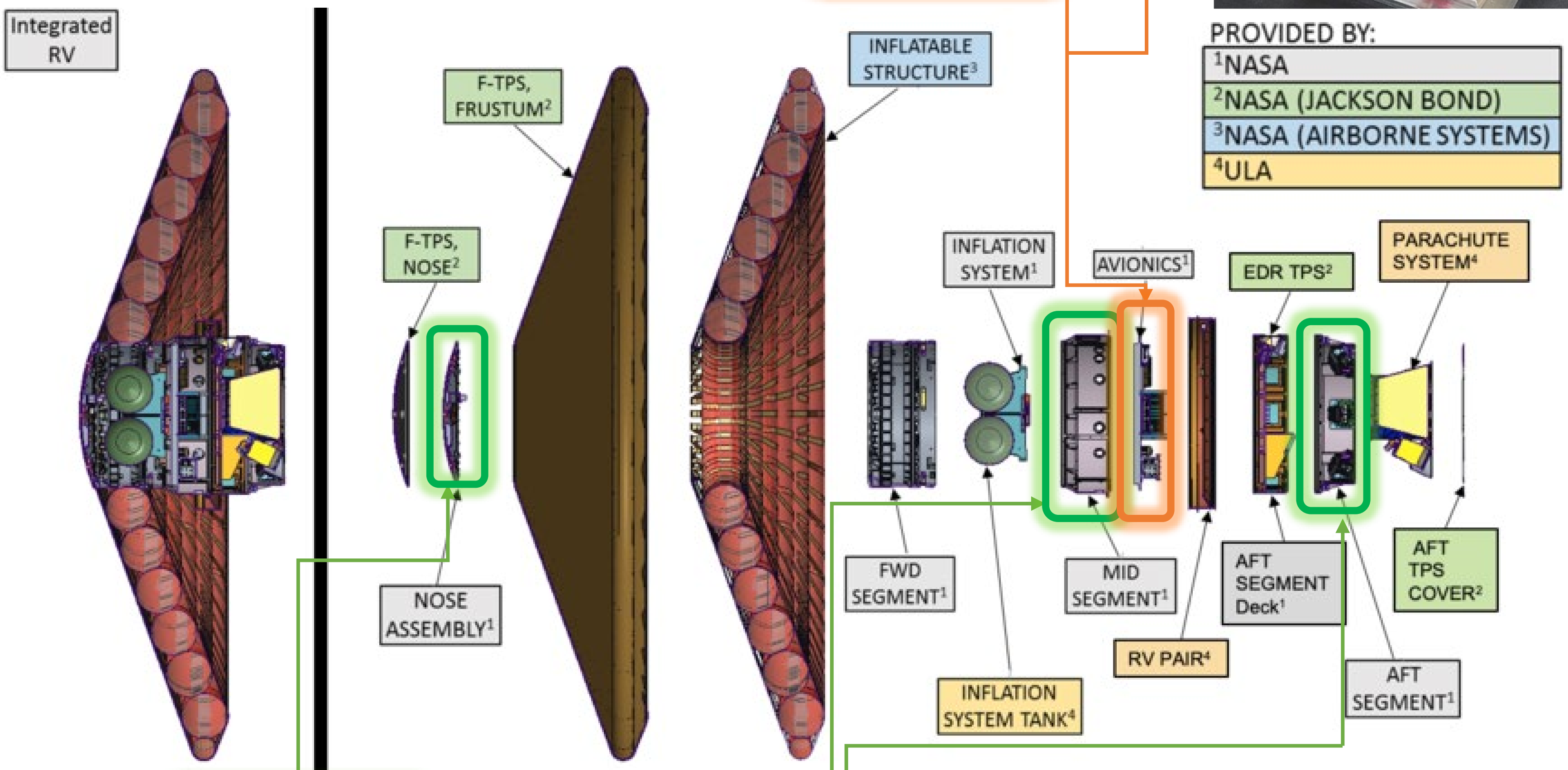
- FOSS conducted and pass all environmental testing*
  - EMI testing
  - Burn-In
  - Thermal vacuum cycling (TVAC)
  - Vibration testing
- Launched on Nov 1st 2022

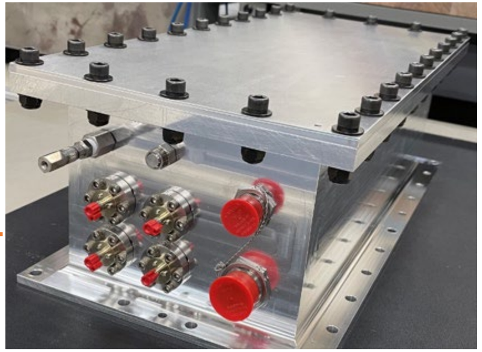
Launch Capable FOSS Specifications	
Parameters	**Units**
Fiber channel count	4
Max sensing fiber length	40 ft
Max patch cable length from system	≈100 ft
Fiber type	Single-mode fiber (SMF)-28
Max no. of sensors/fibers	2,000
Max Sample rate	50 Hz
Onboard storage	32 GB
Interface	Gigabit Ethernet
User Interface Protocol	transmission control protocol (TCP)/internet protocol (IP)
Operational Communication Protocol	user datagram protocol (UDP)
Power	70 W at 28 VDC
Weight (including enclosure)	38 lbs
Size (application specific)	18.15 in by 8.625 in by 6.25 in

* *Detail of testing – SENS-03 session, Thursday (tomorrow)*

FOSS On Board

Compact FOSS System Located on Avionics[1]





FOSS Fiber locations

LOFTID contained 3 FOSS fibers:

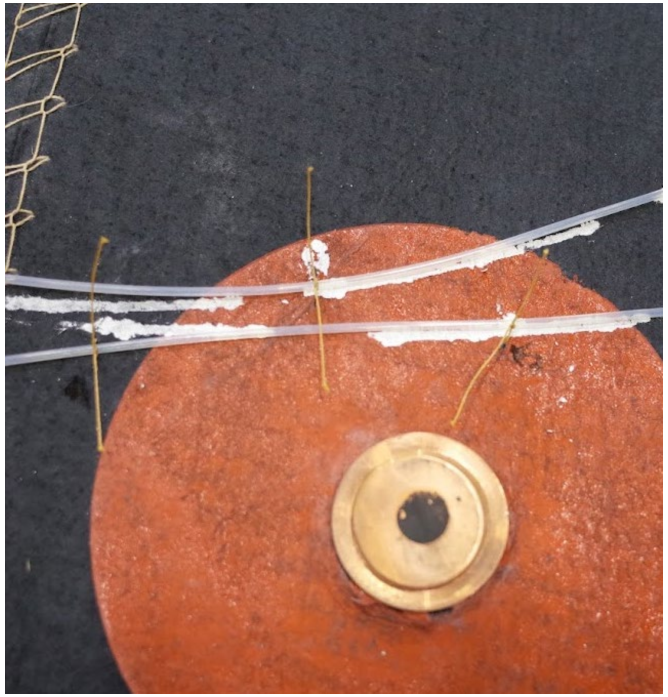
1. Located on the NOSE ASSEMBLY[1] in a modified spiral configuration with concentric circles in a deorbiting pattern
2. Located on the MID SEGMENT[1] going straight down the side
3. Located on the AFT SEGMENT[1] going straight down the side

The Compact FOSS System was located on the AVIONCS[1] section

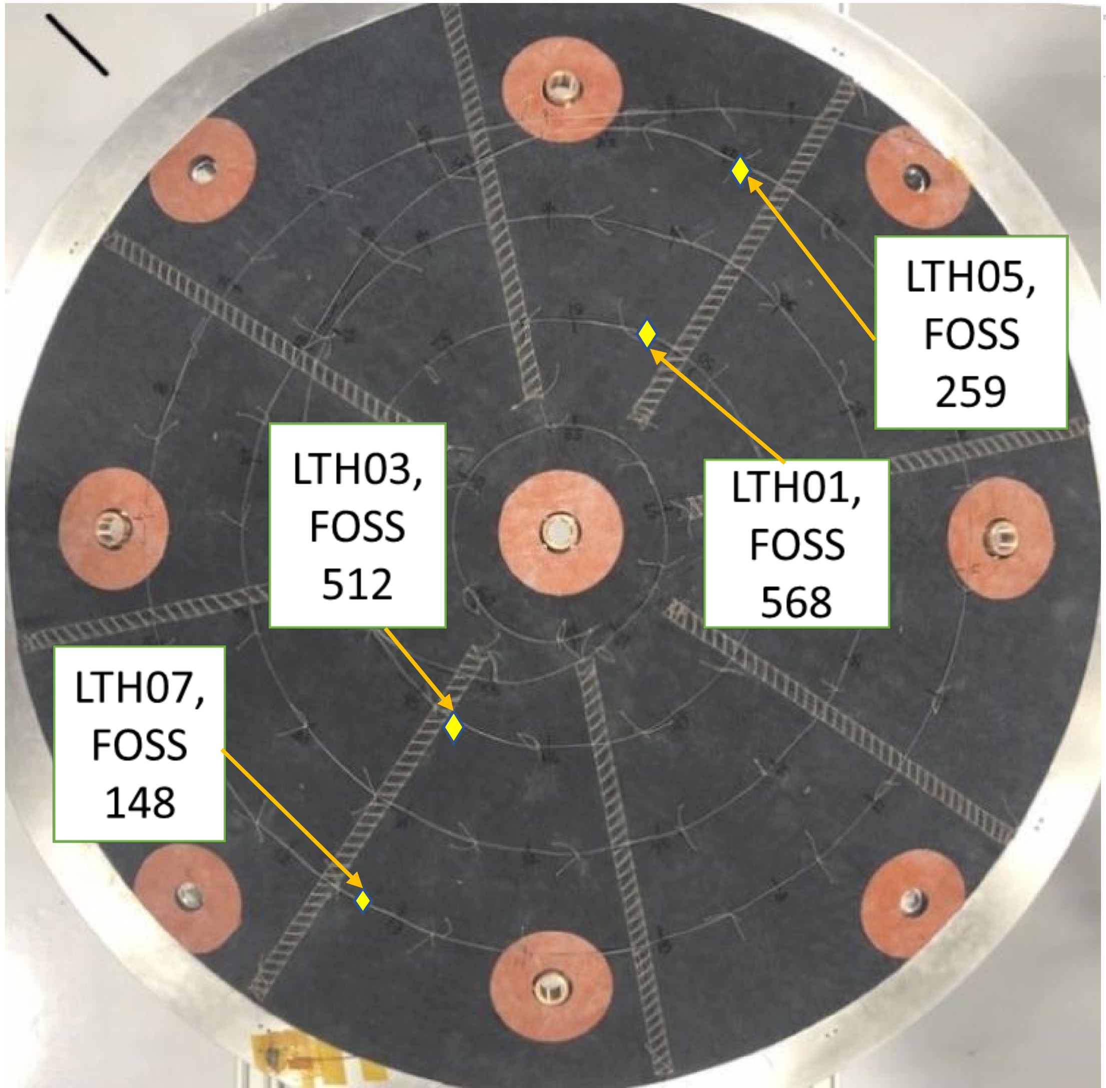
Thermal measurements were taken with the Compact FOSS system and with traditional Thermocouples, the resulting data was then compared and confirmed the accuracy of the FOSS system, even in space flight and reentry conditions.

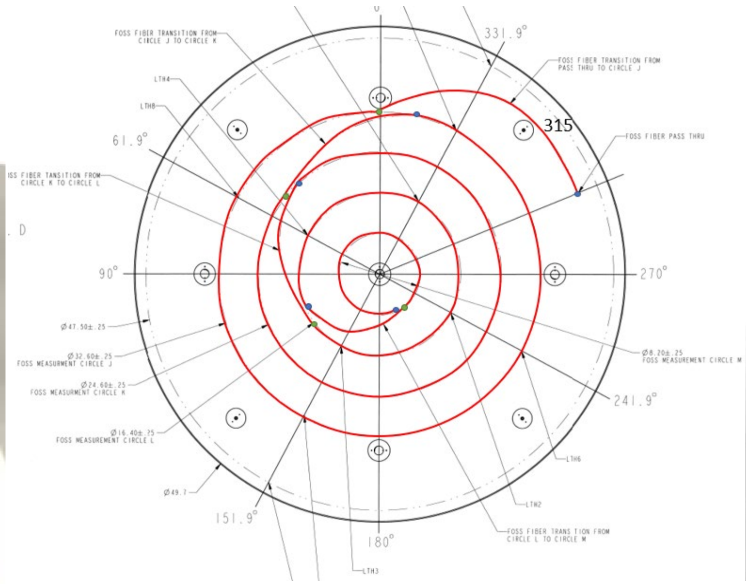
Flight FOSS Fiber Install

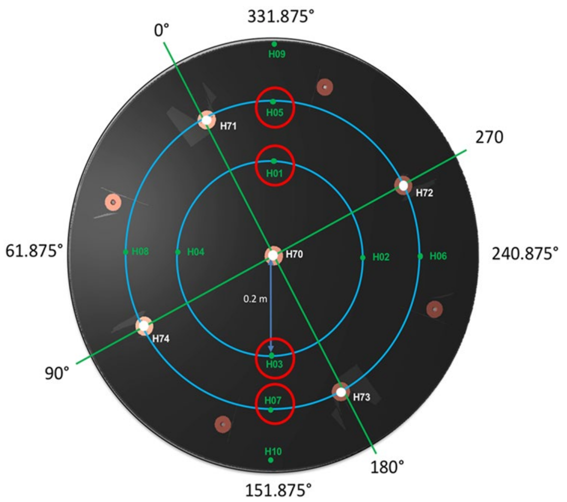
- After installation of underlying insulator layers the FOSS stencil is put in place.
- Then location marking indicators are created
- A ring needle was used to put tie down thread in place at each tack point
- Those threads were then used to tie the FOSS Fiber in place



Identify FOSS FBG and Thermocouple Locations



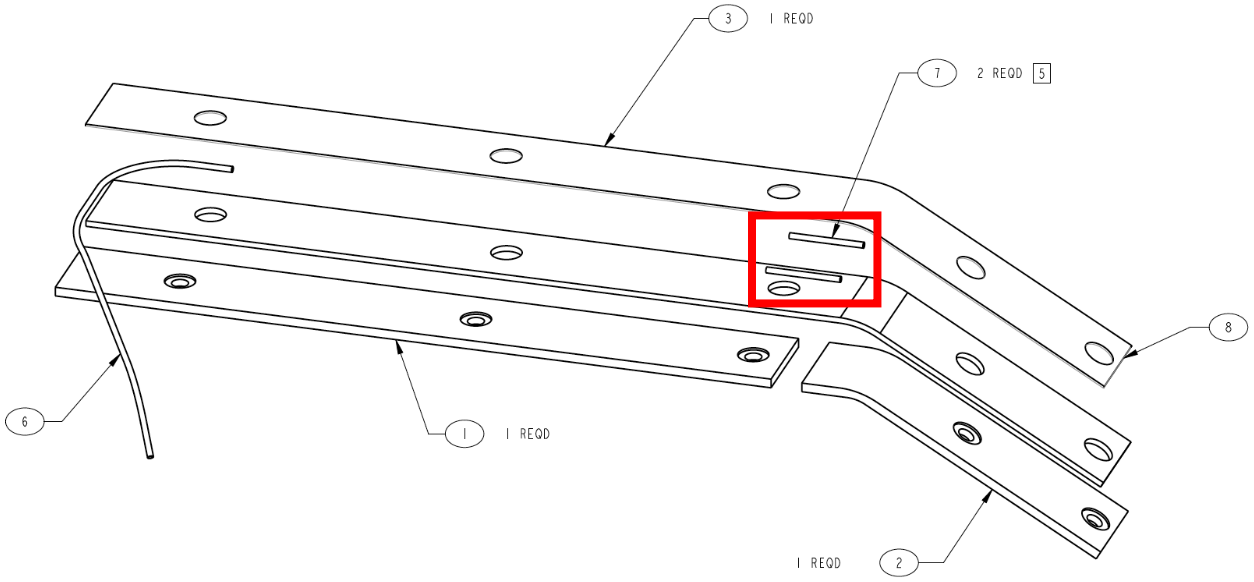


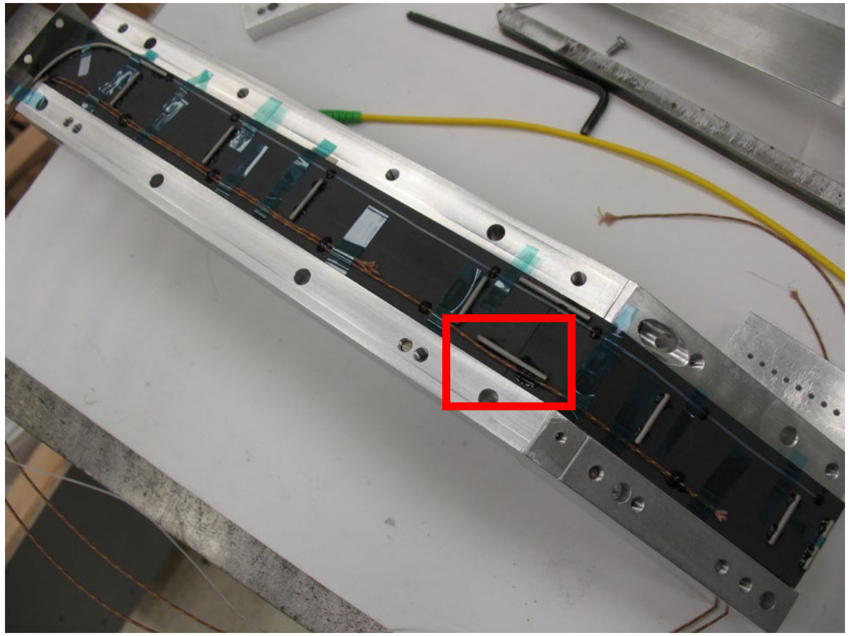


Rotated Thermal couple locations.

- Each FBG sensors is verified via a bench-top FOSS system and a heat gun to trigger temperature change and labelled.
- Each 10th FBG location is marked on to nosecone, where the position can be identified within +/- ¼" accuracy.

Extra credit – FOSS on Mid and Aft portion on LOFTID payload

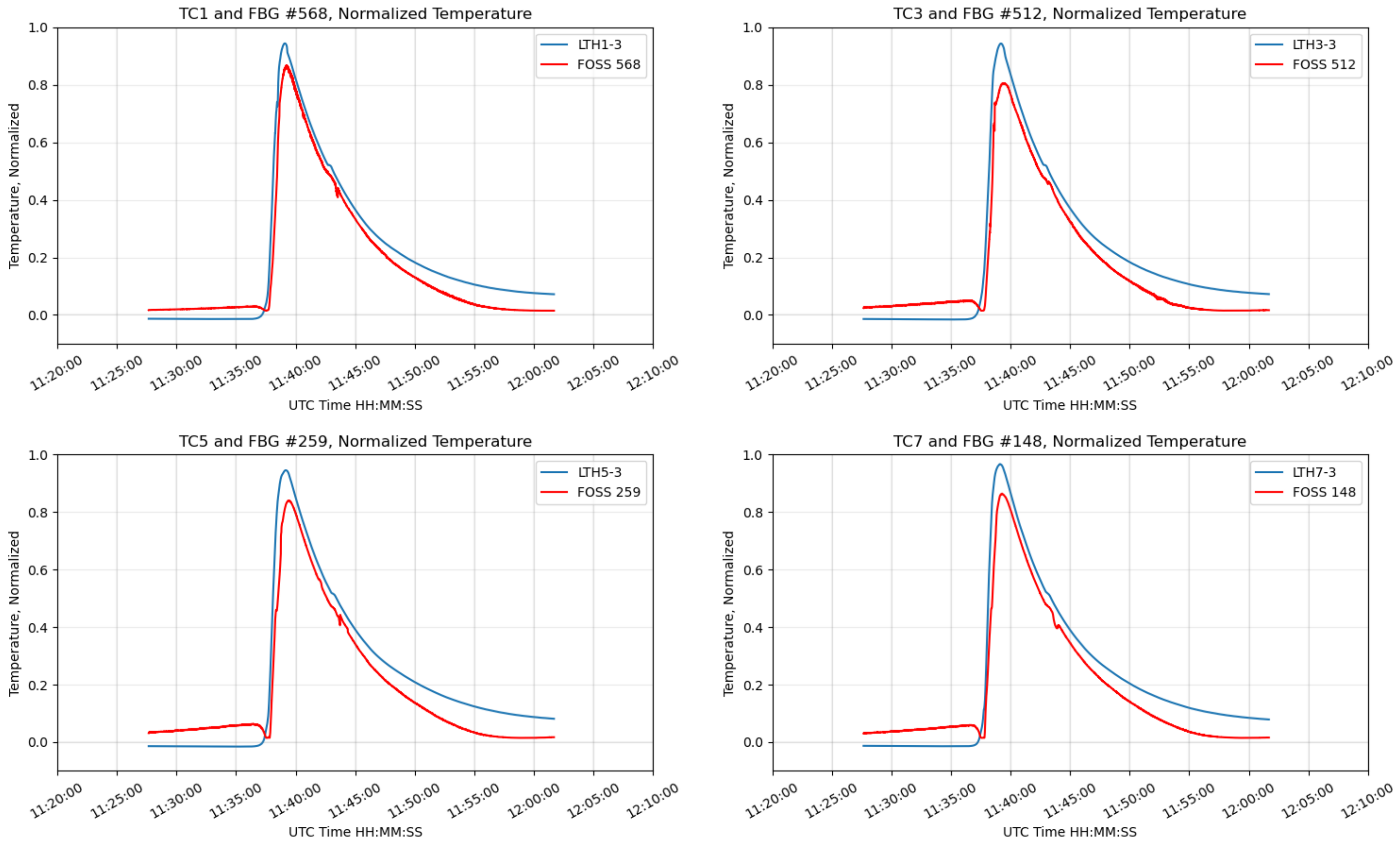


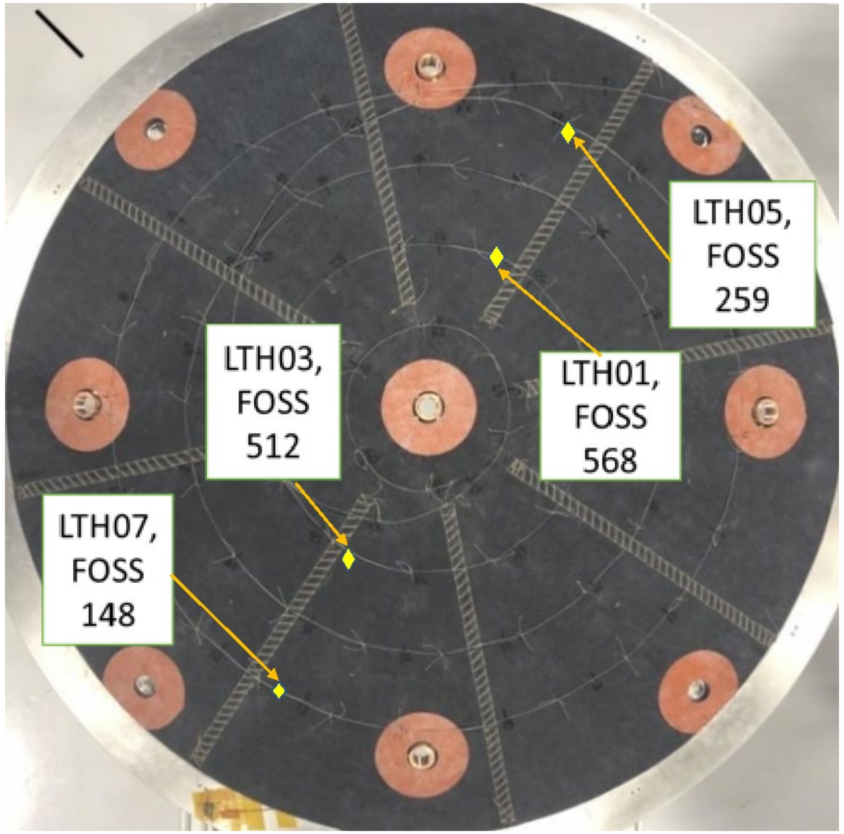


- Fiber sensors were also installed straight down the side of the mid and aft sections of the LOFTID payload, as part of the embedment experiment.
- Fiber sensors are sandwiched between 2 pieces of aluminum plates, with reinforcement tubing (OD of 33mils) to provide structural support

Video of FOSS Data Thermal Mapping

FOSS Data vs thermocouple

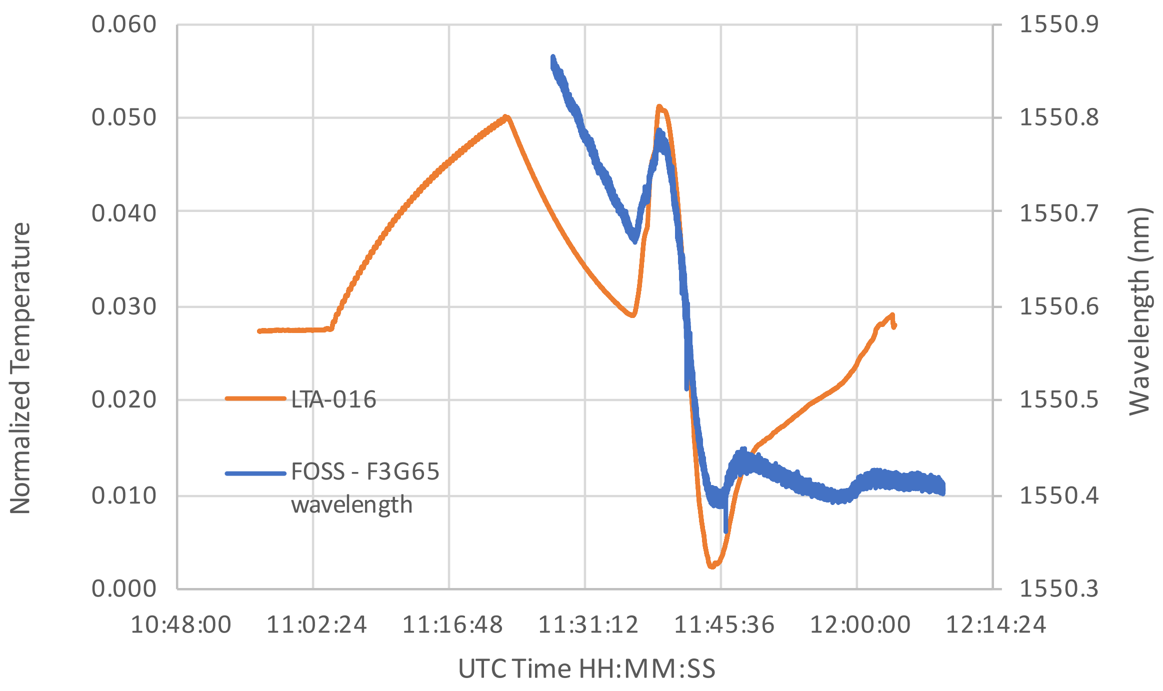


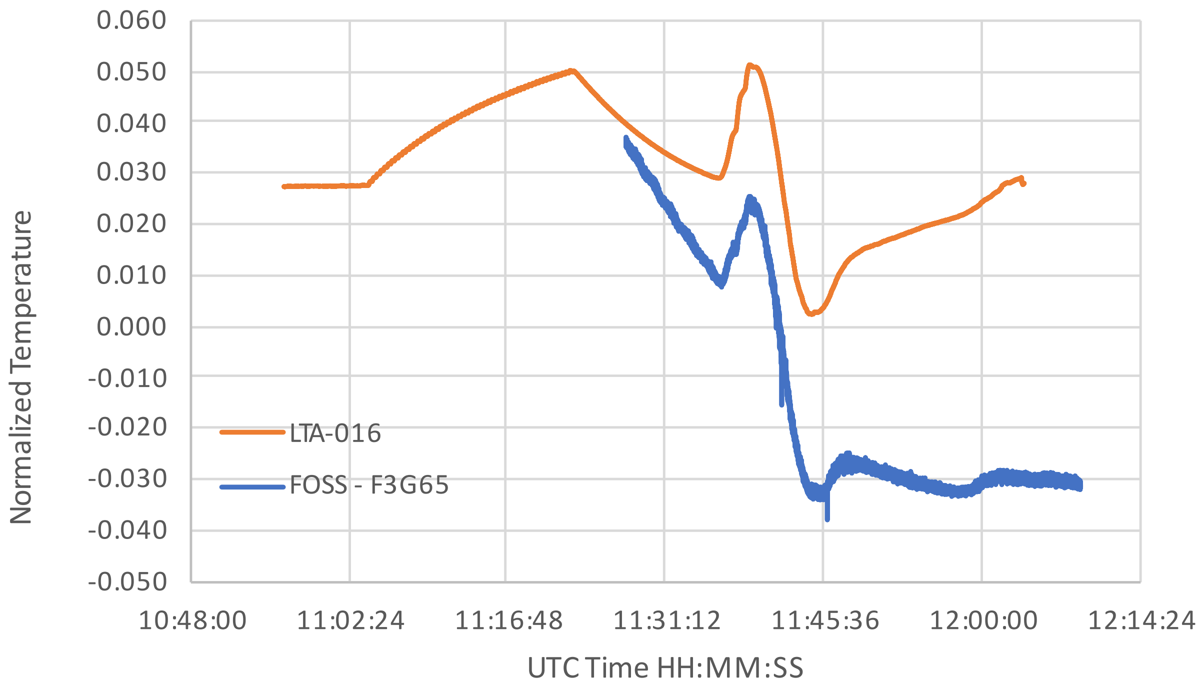


Comparing data from thermocouples (Blue) and nearest collocated FBG (Red)

- The agreement proves the accuracy of the FOSS data.
- Note: comparative accuracy may have discrepancies due to the FOSS fiber being under protective layers and the TCs being on top of those layers.

FOSS data on mid and aft portion





- Profile - Recorded data matched well between the TC versus representative FOSS data.
- Payload does not experience any elevated temperature - effectiveness of the inflatable heatshield.
- Temperature data discrepancy results in the fiber data showing a negative temperature reading.
  - Maybe caused by apparent strain component from novel embedding of fiber into the IML of payload panel

Conclusion

- The ruggedized FOSS system successfully acquired multiple measurements contiguously at 20 samples per second
- The fiber placed behind the FTPS rigid aeroshell provided 1,110 temperature data.
- On the rigid aeroshell, co-located FOSS FBGs and thermocouples were in agreement with reasonable tolerance for difference in locational protections.
- Fibers from the mid and aft sections of the payload confirmed that the overall temperature is steady, proving the effectiveness of the heat shield.
- The system has <u>seawater residue from the splashdown</u> but proved to be fully operational due to its hermetic design.
- PS – FOSS system still functions as of today!